Surface topography of retrieved PCA acetabular liners: proposal of a novel wear mechanism

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It is commonly accepted that the long term loosening, and subsequent failure, of a total hip replacement is due an osteolytic response to particulate wear debris [1]. Moreover, this immunological response seems to be dependent on the morphology of the debris produced [2]. Studies on wear debris have indicated that the distribution of particle size may be bimodal with particles of tens of micrometers in size in addition to sub-micrometer particles [3]. Thus, the contribution of the larger particles to the wear volume may be substantial despite a lower frequency [4]. The influence of femoral head roughness on the wear of the socket is widely recognized [5]. However, the effect of the socket surface topography on debris production has had little investigation.

This study assesses the surface of the acetabular liner using a combination of techniques. The use of differential interference contrast (DIC) microscopy and scanning electron microscopy (SEM) allows a qualitative examination, while non-contacting profilometry gives quantitative information on the topography.

The porous coated anatomic (PCA) total hip replacement (Howmedica) was chosen as it gave the opportunity to study the mechanisms of wear without the influence of cement ingression. Twenty explanted acetabular liners were retrieved at revision surgery; ten were of the one-piece design and ten of the modular "snaplock" type. The patient group consisted of 11 men and 9 women with a mean age of 41.2 ± 12.9 y. The mean life of the prosthesis was 5.7 ± 1.9 y. The reasons for primary surgery were rheumatoid arthritis in 8 cases, osteoarthritis in 4 cases, congenital displaysia of the hip (CDH) and ankylosing spondylitis accounted for a further 6 cases, with the remaining being for trauma.

A preliminary study was undertaken using a non-contacting interference profilometer to assess the surface (Zygo NewView 100). A ten times objective lens was used, giving a coverage of 730 μm by 550 μm which represents a horizontal resolution of 2.3 μm per pixel. The vertical resolution of this instrument was 0.1 nm. Form error was removed as twin orthogonal cylinders. The information obtained was used to define a filtering wavelength of 50 μm. The two topographical parameters selected to describe the waviness and roughness of the surface were the root mean square deviation and maximum peak height values: these are defined in Fig. 1. The explanted liners were measured quantitatively at six positions in the articulating region and three in the periphery.

Descriptive examination of the cups at low magnifications was conducted using a differential interference contrast microscope (Ziess Axiotech). Magnifications of 100 and 200 times allowed the wear features over large areas to be assessed.

Selected cups were gold sputter coated prior to microscopic studies using a Joel JSM IC848 scanning electron microscope. A range of magnifications up to $\times 10{,}000$ was used to ascertain the nature of the nanometre scale surface features.

Prior to microscopic assessment it was noted that the worn surface exhibited a highly polished nature. The microscopy provided valuable information on the nature of the ultra heavy medium weight polyethylene (UHMWPE) surface. The grain structure of the UHMWPE was easily distinguishable using the DIC microscope (Fig. 2), however the SEM seemed less capable in this regard (Fig. 3). The width of the grains ranged from under 50 μm to approximately 250 μm. No variation in the distribution of grain sizes was observed between the two liner varieties.

Light scratching was observed in the worn region with no dominant orientation. Occasional deep scratches in the worn region were thought to be attributable to damage sustained during surgery. The unworn region often displayed evidence of deep

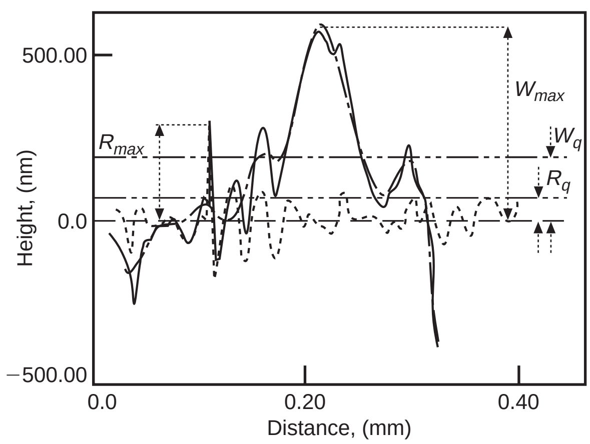

Figure 1 Schematic diagram of roughness parameters.

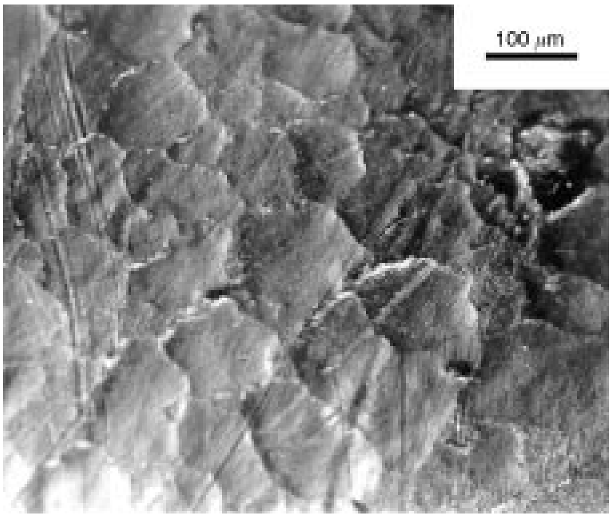

Figure 2 DIC micrograph showing granular nature of acetabular articular surface (×200).

Figure 3 SEM micrograph showing plucked grain site and scratching. Note the lack of detail of the grain structure (×170).

scratching superimposed on the machining marks (Fig. 4).

Subsequent SEM at high magnification allowed images to be obtained at the grain boundary regions (Fig. 5). Deep cracks running along the boundary for hundreds of micrometers were frequently observed. The polyethylene exhibited a rippled texture at the nanometre scale.

The surface features observed were quantified using profilometry, of note were the very low values of root mean square roughness and waviness, R_q and W_q, for the worn region (Table I). Analysis of variance showed highly significant differences be-

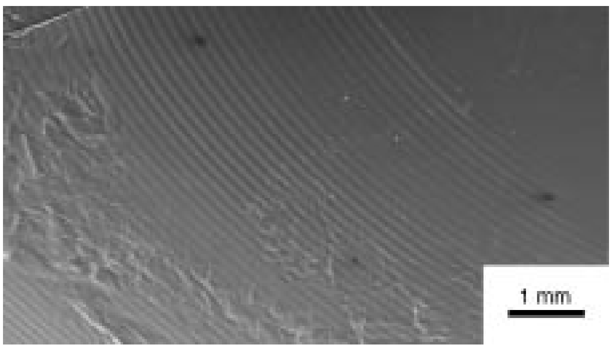

Figure 4 SEM micrograph of periphery of acetabular cup away from articulating region (×15).

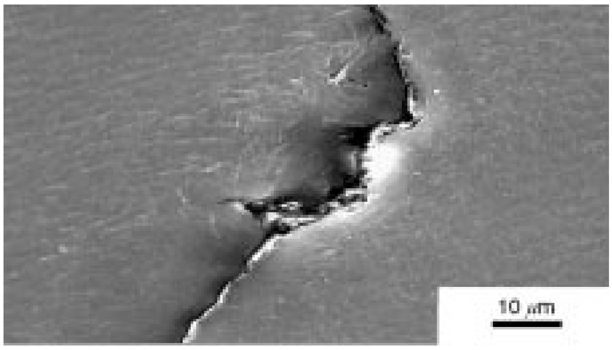

Figure 5 SEM micrograph of grain boundary crack. Note the rippling of the adjacent polyethylene (×2000).

TABLE I Roughness values for worn and peripheral regions

		Median (μm)	Interquartile range (μm)
Worn	*Rq*	0.07	0.03–0.38
	Rpeak	2.19	0.85–17.50
	Wq	0.10	0.05–0.80
	Wpeak	0.47	0.15–5.42
Peripheral	*Rq*	0.39	0.12–1.16
	Rpeak	20.21	6.78–43.30
	Wq	0.91	0.21–1.87
	Wpeak	2.57	1.05–6.34

tween the worn and unworn regions for all the topographical parameters measured.

The surface profilometry revealed the presence of a number of depressions in the surface. These depressions were approximately circular in shape and of the order of 150 μm in diameter and up to 1 μm in depth. These features were only observed in the worn zone and away from the boundary with the unworn region. The depressions were not observed in all the liners assessed.

The analysis of *in vivo* wear debris has shown that the majority of wear particles are sub-micrometer in size [6, 7], with a mode in the range 0.1–0.5 μm [4]. However, the presence of large smooth platelets of 10–100 μm diameter has been observed in the case of wear of UHMWPE by supersmooth counterfaces [3]. It has been reported in a previous retrieval study that the femoral head of the PCA prosthesis remains remarkably smooth during its life [8]. It may then be hypothesized that these particles would be produced by the *in vivo* articulation of the currently studied prostheses.

Cooper *et al*. [9] suggested that the large particles may be caused by the fatigue and detachment of long wavelength asperities from the surface. This theory relies on the stress levels in the asperity being large enough to fatigue the polyethylene before it is abraded. The topographical studies on which this theory are based state that "peaks with an amplitude of up to 10 μm" are observed having a wavelength of approximately 200 μm. Our studies show that the maximum peak height of the waviness has a median amplitude of 0.47 μm and a range of wavelengths in the order of 100–300 μm. The strains achieved in the undulations revealed by our studies would be lower in magnitude, hence a very large number of cycles would be needed to achieve the fatigue limit of the UHMWPE. It is doubtful whether this would happen prior to the removal of this material by microadhesion or abrasion. Cooper's wear model would also be self-limiting in that once the asperities are detached the surface would be devoid of any long wavelength asperities. Therefore, the mechanism by which this mode of wear is created has been removed.

The treatment of UHMWPE as a homogenous continuum by Cooper's model may not be justified. The presence of intergranular defects in both finished components and the bulk UHMWPE prior to manufacture has been reported by many authors [10]. The microscopic investigation reported in this paper clearly shows the grain structure at the surface of the UHMWPE and thus the fatigue model of Cooper *et al*., which does not exploit the intergranular weaknesses of the UHMWPE, must be limited.

The large particle dimensions are strikingly similar to those of the depressions seen in the topographical studies presented in this paper. This suggests that the depressions observed are caused by the release of a platelet wear particle from the surface. The mechanism by which this would happen is illustrated in Fig. 6. The bulk of the UHMWPE is removed by microadhesion or abrasion, creating the sub-micrometer sized wear particles. However, when only a portion of an individual grain remains it is vulnerable to fatiguing of the grain boundary region by shear stresses. This may quickly result in the failure of the mechanical interlock between the grains which would facilitate the removal of the remaining portion of the grain by a plucking or rolling motion.

The failure to observe the depressions in all the liners may reflect the random nature of the selection of sites assessed. This mode of wear may be restricted to a certain set of tribological conditions or region of the liner. Alternatively, the variation in the quality and granular integration of the UHMWPE could explain this phenomenon.

This model exploits the granular structure of the UHMWPE by fatiguing the bulk material at its weakest point, it is capable of producing the surface topography observed and the wear debris predicted.

Further work, including wear debris analysis and finite element analysis of the stresses imposed on the UHMWPE asperities, is needed to substantiate this hypothesis.

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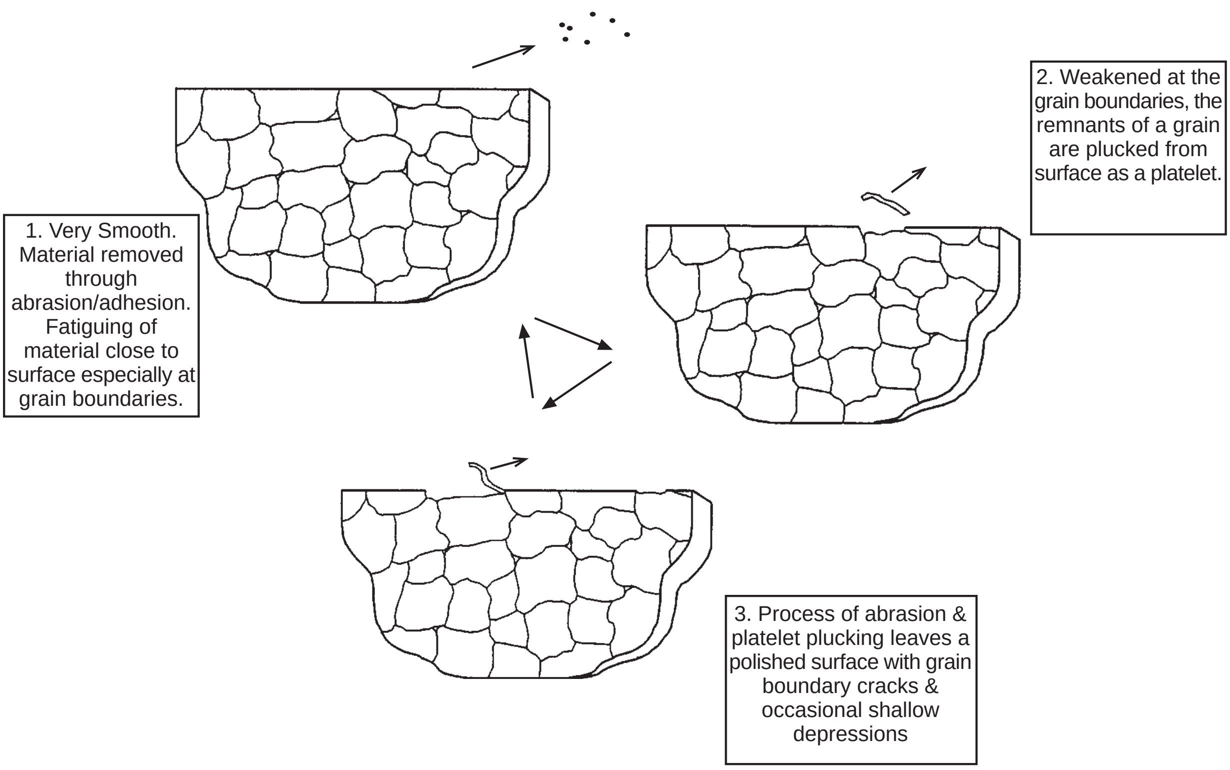

Figure 6 Schematic diagram of a section through part of the UHMWPE acetabular liner. The diagram describes the proposed wear mechanism. Not to scale.

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